DESIGN OF SEGMENTAL ROTOR AND NON-OVERLAP WINDINGS IN SINGLE-PHASE FEFSM FOR LOW TORQUE HIGH SPEED APPLICATIONS

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Dedicated to

my beloved father and mother,

Haji Omar Ismail and Hajah Maznah Ali,

my wife and my children,

Suriani Othman, Muhammad Yusuff, Muhammad Luqman and Nur Insyiraah

my siblings and my friends.

Thank you for your love, prayer, and support.

I love you all deeply.

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ABSTRACT

In this research, a new structure of single-phase field excitation flux switching motor (FEFSM) using segmental rotor structure and non-overlap windings arrangement is proposed in order to overcome the drawbacks of low torque and small power performances due to their longer flux path in the single-phase FEFSM using salient rotor structure and overlap windings arrangement. The objectives of this study are to design, analyse and examine performance of the proposed motor, to optimize the proposed motor for optimal performances, and to develop the proposed motor prototype for experimental performance validation. The design and analyses thru 2D-finite element analysis (FEA) is conducted using JMAG Designer version 15, while deterministic optimization method is applied in design optimization process. To validate the 2D-FEA results, the motor prototype is developed and tested experimentally. Based on various rotor poles analysis, a combination of 12 pole 6 pole (12S-6P) has been selected as the best design due to their highest torque and power capability of 0.91 Nm and 277.4 W, respectively. Besides, the unbalance armature magnetic flux of the proposed FEFSM using segmental rotor has been resolved by using segmental rotor span refinement. The balanced armature magnetic flux amplitude ratio obtained is 1.002, almost 41.2% reduction from the initial design. In addition, the optimized motor has increased maximum torque and power by 80.25% to 1.65 Nm, and 43.6% to 398.6W, respectively. Moreover, copper loss of the optimized design has decreased by 9.7%%, hence increasing the motor efficiency of 25.3%. Finally, the measured results obtained from the prototype machine has reasonable agreement with FEA results, proving their prospect to be applied for industrial and home appliances.

ABSTRAK

Dalam kajian ini, struktur motor fluks teralih medan pengujaan (FEFSM) fasa-tunggal baru yang menggunakan struktur pemutar bersegmen dan susunan lilitan tidak bertindih dicadangkan untuk mengatasi masalah prestasi daya kilas dan kuasa yang rendah yang disebabkan oleh laluan fluks yang panjang menghasilkan fluks magnetik yang lemah di dalam FEFSM fasa-tunggal yang menggunakan struktur pemutar menonjol dan susunan lilitan bertindih. Objektif kajian ini adalah untuk merekabentuk, menganalisis dan mengkaji prestasi motor yang dicadangkan, untuk mengoptimumkan motor yang dicadangkan bagi mendapatkan prestasi optimal, dan untuk membangunkan prototaip motor yang dicadangkan bagi tujuan pengesahan prestasi secara eksperimen. Reka bentuk dan analisis adalah dijalankan menerusi 2D-analisis unsur terhingga (FEA) dengan menggunakan JMAG Designer versi 15, manakala kaedah pengoptimalan deterministik adalah digunakan dalam proses pengoptimuman reka bentuk. Untuk mengesahkan keputusan yang diperolehi daripada FEA, prototaip motor adalah dibangunkan dan diuji secara eksperimen. Berdasarkan analisis pelbagai kutub pemutar, kombinasi 12 celah 6 kutub (12S-6P) telah dipilih sebagai rekabentuk terbaik kerana mempunyai keupayaan tork dan kuasa tertinggi, masing-masing sebanyak 0.91 Nm dan 277.4 W. Selain itu, fluks magnetik armatur yang tidak seimbang pada FEFSM dengan pemutar bersegmen yang dicadangkan telah diselesaikan dengan menggunakan penghalusan rentang pemutar segmen. Nisbah amplitud fluks magnatik armatur yang diperoleh adalah 1.002, menurun sebanyak hampir 41.2% dari reka bentuk awal. Sebagai tambahan, tork dan kuasa motor yang dioptimumkan telah meningkat, masing-masing sebanyak 80.65% kepada 1.65 Nm, dan 43.6% kepada 398.6W. Di samping itu, kehilangan kuprum rekabentuk yang dioptimumkan adalah menurun sebanyak 9.7%, oleh itu kecekapan motor telah meningkat sebanyak 25.3%. Akhir sekali, keputusan yang diukur dari motor prototaip adalah sejajar dengan keputusan FEA, membuktikan prospek motor untuk digunakan pada peralatan industri dan perkakas elektrik rumah.

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LIST OF SYMBOLS AND ABBREVIATIONS

A_g	-	Air gap
A_w	-	Area of wire
α	-	Filling factor
B	-	Magnetic field
E_B	-	Bottom end coil length
E_{ind}	-	The voltage induced in the turn of the coil
E_T	-	Top end coil length
e_k	-	Phase back-emf
f_e	-	Electrical frequency
f_m	-	Mechanical rotation frequency
H	-	Stack length
I_a	-	Armature coil current
I_e	-	Field excitation coil current
i_k	-	Phase current
J_a	-	Armature current density
J_e	-	Field current density
k	-	Phase designation
L	-	Length of 1 turn
L_k	-	Phase winding inductance
L_{si}	-	Circumference of inner stator
m	-	Natural number
η	-	Efficiency
N	-	Number of turns of wire in coil
N_{cte}	-	Electrical angle of rotation for each period of cogging torque
N_{ctp}	-	Number of periods
N_e	-	Number of FE coils

N_r	-	Number of rotor poles
N_s	-	Number of stator slots
n_s	-	Rotational speed in revolution per minute
P	-	Instantaneous power
P_{ac}	-	Armature coil copper loss
P_c	-	Copper loss
P_{fec}	-	FEC copper loss
P_i	-	Iron loss
P_o	-	Output power
P_r	-	Rotor iron loss
P_s	-	Stator iron loss
R	-	Resistance
r_{ir}	-	Inner radius of rotor
r_{or}	-	Outer radius of rotor
r_{sbi}	-	Radius of stator back inner
r_{si}	-	Inner radius of stator
r_{so}	-	Outer radius of stator
S_a	-	Armature coil slot area
S_e	-	FEC slot area
S_r	-	Split ratio
t	-	Time
T_e	-	Electromagnetic torque
T_d	-	Torque density
T_{exc}	-	Excitation torque
T_{rel}	-	Reluctance torque
V	-	Volume
W	-	Weight
w_r	-	Rotor tooth width
w_s	-	Stator tooth width
ω_r	-	Rotational speed in radian per second
θ	-	Electrical angular position of rotor
θ_{seg}	-	Segmental rotor span
ρ	-	Copper resistivity

φ	-	Flux
Ψ_{exc}	-	Flux linkage due to field excitation
ABC	-	Artificial Bee Colony
ACW	-	Anti-clockwise
AFPMSM	-	Axial flux permanent magnet machine
ASMA	-	Artificial bee colony-strength pareto and evolutionary algorithm
CAD	-	Computer aided design
CGA	-	Conjugate gradient algorithm
CNC	-	Computer numerical control
CW	-	Clockwise
DC	-	Direct current
DE	-	Differential evolution
DFDSM	-	Doubly fed dual stator motor
DOM	-	Deterministic optimization method
Dy	-	Dysprosium
EA	-	Evolutionary algorithm
EDA	-	Estimation of distribution algorithm
EV	-	Electric vehicle
FE	-	Field excitation
FEA	-	Finite element analysis
FEFSM	-	Field excitation flux switching motor
FEM	-	Finite element method
FEC	-	Field excitation coil
FSM	-	Flux switching motor
GA	-	Genetic algorithm
GBA	-	Gradient based algorithm
HCF	-	Highest common factor
HE	-	Hybrid excitation
HEFSM	-	Hybrid excitation flux switching motor
IM	-	Induction motor
IOA	-	Intelligent optimization algorithm
IPMSM	-	Interior permanent magnet synchronous motor
MOA	-	Multi-objective algorithm
Nd	-	Neodymium

NSGA	-	Non-dominated sorting genetic algorithm
PM	-	Permanent magnet
PMFSM	-	Permanent magnet flux switching motor
PMSG	-	Permanent magnet synchronous generator
PMSM	-	Permanent magnet synchronous motor
PSO	-	Particle swarm optimization
RS	-	Response surface
Rt	-	Rotor tooth
Seg	-	Segment
SPEA	-	Strength pareto evolutionary algorithm
SQP	-	Sequential quadratic programming
SRM	-	Switched reluctance motors
St	-	Stator tooth
THD	-	Total harmonic distortion
TM	-	Taguchi method
TS	-	Tabu search
WA	-	Winding arrangements

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Currently, most of the commercial applications that require low torque and high speed performances such as blower, exhaust fan, compressor motors, pumps, and fan are using induction motors (IMs) as their main prime mover [1], [2]. The specifications of single-phase IMs used in commercial applications are illustrated in Table 1.1 [3]. Induction motor's rotor can be either wound type or squirrel-cage type. For the wound type, winding is located on the rotor and stator, while for squirrel-cage winding is placed only on stator. Consequently, rotor not robust, and heat temperature of rotor is easily increased, resulting in heat accumulated in the middle of motor [4].

Another motor that commonly used in electrical appliances is DC motors due to its advantages of high power density and high efficiency [5]. However, DC motors are suffering from usage of commutators and brushes. This weakness makes the DC motors less reliable and is not suitable for maintenance-free operation. Therefore, some researchers have developed the switched reluctance motors (SRMs) because of its structural simplicity, high efficiency, low cost, and control flexibility compared to IM [6], [7]. The SRM drive system is an advanced control technology which the conventional AC and DC motors drives do not have [8]. However, the SRMs have demerits of high torque ripple, high noise, and vibrations. Besides, the use of position sensor in SRM has increased the drives system complexity and makes the system less reliable [9].

Table 1.1: Single-phase induction motor specifications [3]

Items	Parameters
Input voltage (Volt)	240
Frequency (Hz)	50
Rated power (W)	60
Rated torque (Nm)	0.4
Range of speed (rpm)	1455-1465
Outer diameter of stator (mm)	75
Outer diameter of rotor (mm)	44.5
Stack length (mm)	20.3
Length of air gap (mm)	0.25
Weight (kg)	0.91

In order to improve torque performance and efficiency of electric motors, flux switching motors (FSMs) originated from the blend of switched reluctance motor and inductor alternator is introduced. The first concept of FSM was founded and published in the mid-1950s. The main features of FSM are all active parts such as coil windings and permanent magnet are placed on stator, a single piece of rotor structure, and free from brush maintenance [10]. Over the past three decades, numerous FSM topologies have been developed for various applications, ranging from low-cost domestic appliances, automotive, wind power, and aerospace [11]. Generally, FSM can be categorised into three groups: permanent magnet flux switching motor (PMFSM), field excitation flux switching motor (FEFSM), and hybrid excitation flux switching motor (HEFSM). Both PMFSM and FEFSM have only permanent magnet (PM) and field excitation coil (FEC), respectively as their main flux sources, while HEFSM combines both PM and FEC as its main flux source. Compare with other FSMs, FEFSM has preferences of low cost, simple construction, magnet-less machine, and variable flux control capabilities reasonable for different performances. Besides, FEFSMs have the advantage of cost-saving materials as the PM on stator used in PMFSM is replaced by excitation from FECs [12].

Figure 1.1 illustrates the basic operation of FEFSM. Considering Figure 1.1 (a), the excitation of the field and armature windings at positive current creates a flux vector in the north-westerly direction and north-easterly direction, respectively. The combined flux generated by the two coils caused a flux moving vertically upwards and the rotor aligned itself with a pair of vertical stator. Moreover, Figure 1.1 (b) illustrates the current in the armature winding is reversed, while the FEC winding continues being

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